White Paper on

Proposed Development of a Joint Scientific - Operational Arctic-Wide Sea Ice Product

Prepared for

Dr. S. Gogineni
NASA Polar Programs

Prepared by

K.C. Partington[1] and K. Steffen[2]

[1]National Ice Center,
4251 Suitland Rd.,
Washington, D.C. 20395
(kpartington@natice.noaa.gov)

and

[2]Cooperative Institute for Research In Environmental Science
Campus Box 216,
Boulder, CO, 80309-0216
(koni@seaice.colorado.edu)

14 April, 1998

Distribution

NIC	CDR. D. Martin, Mr. D. Benner, Ms. C. Bertoia
FNMOC	CAPT. D. Mantner, Dr. J Haferman, Mr. M. Clancy
NOAA	Ms. H. Wood, Dr. M. Van Woert
NSF	Dr. T. Pyle
NRL	Dr. E. Hartwig, Dr. R. Preller, Dr. G. Poe
NASA	Dr. S. Gogineni
ONR	Dr. T. Curtain, Dr. D. Conley, Dr. C. Paulsen, Dr. M. Colton
NO96	Mr. R. Godin
SPAWARS	Dr. S. Payne, CAPT. C. Hopkins
USARC	Dr. G. Brass
NSIDC	Dr. R. Barry, Dr. F. Fetterer

Abstract

This document presents a plan for implementation of a high quality Arctic-wide sea-ice product, based on data assimilation techniques and coordinated integration of newly available and planned satellite and ground sensor observations. It is recommended strongly that a joint-agency program be established with an oversight committee that manages the program. The benefits of this program will include development of a high quality geophysical product that serves both the scientific and operational communities, pooling of scarse resources, wider return on investment and a long-term strategy for sea ice research.

INTERNET DOCUMENT INFORMATION FORM

A . Report Title: Proposed Development of a Joint Scientific-Operational Arctic-Wide Sea Ice Product

B. DATE Report Downloaded From the Internet: 07/22/99

C. Report's Point of Contact: (Name, Organization, Address, Office Symbol, & Ph #):

National Ice Center
Federal Building #4
4251 Suitland Road
Washington, Dc 20395

D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

F. The foregoing information was compiled and provided by:
DTIC-OCA, Initials: __VM__ **Preparation Date 07/22/99**

The foregoing information should exactly correspond to the Title, Report Number, and the Date on the accompanying report document. If there are mismatches, or other questions, contact the above OCA Representative for resolution.

Development of a joint scientific - operational Arctic-wide sea ice product

List of Contents

Acknowledgements

This document was prompted by discussions at the meeting entitled "Sea ice monitoring into the next millenium: workshop to evaluate new approaches to sea ice observation", held in Boulder on 3-5 December, 1997, and by discussions with Drs. R. Thomas and S. Gogineni of NASA and Dr. T. Curtain of ONR. It makes use of material from all participants at that meeting, for which the authors are grateful. In particular, the authors would like to thank the sponsors and organizers of that meeting as well as the contributors and editors of the White Paper which resulted from the workshop. Particular reference must be made to Dr. R. Errico of NCAR who provided a most useful introduction to the techniques of data assimilation.

Development of a joint scientific - operational Arctic-wide sea ice product

1. Introduction

Understanding the large-scale distribution and characteristics of the sea-ice cover in the Arctic has been a major objective of both the scientific and operational sea-ice communities for many years. For the scientific community, the primary motivation is to define the key factors that influence decadal-scale variations in sea-ice coverage. For the operational community, the motivation is to obtain early season indicators of ice conditions and to have guidance in producing higher-resolution regional analyses. What is often overlooked is that fact that the information requirements of these two communities overlap to a considerable degree at this "global" scale of coverage (with a spatial resolution of the order of 10 km). Given this strong, broadly-based and long-standing interest, it is important to ask how far we have come towards achieving the goal of being able to monitor the state of the Arctic reliably and accurately.

The development of space-borne passive microwave sensors in the 1970s represented a significant step forward in the development of this capability, and many of the techniques which form the basis for sea-ice models were also developed during that decade. However, although new space-borne sensors (such as synthetic aperture radar), ground observations (such as those provided by the International Arctic Buoy Program) and increasingly reliable weather fields (such as those from ECMWF and FNMOC) have appeared since then, there has been remarkably little development in the capability to combine these resources to provide a high quality, synthesized Arctic-wide sea-ice product. Yet, the implementation of such a product would mark a major milestone in the move towards maturity of the sea-ice monitoring community and would have ramifications well beyond the field of sea-ice research.

With new sensors planned for near real time use in the next year (e.g. MODIS and QUICKSCAT), and new Navy funding being directed towards an upgrade of the operational Navy sea-ice model (PIPS), it is timely to initiate a joint agency program for the development of an Arctic-wide sea ice product. This will make use of data assimilation techniques that have been tried and tested within numerical weather prediction, and will provide a clearly defined route for research techniques to be migrated into the operational environment. Only through a program of this nature and scale can full use be made of the technologies that are available to the sea-ice community.

The importance of such an initiative was recognized in the recent white paper on "Sea-Ice Monitoring into the Next Millenium" (Weaver, 1998). That white paper was aimed at pointing the way forward for wide coverage sea-ice monitoring, and ends by saying that "...the joint development of a scientific /operational global sea ice product is strongly encouraged to make more efficient use of resources". This document outlines how this recommendation may be implemented.

2. Objective and Benefits

The aim of this document is to present a plan for development of an Arctic-wide sea-ice product, and to solicit a combination of resources and a willingness to cooperate from agencies that have an interest in the high latitude regions. **This will build on, and integrate with, new investment in sea-ice models which is being undertaken by the Navy.** The desired outcome of this initiative is for the announcement of a joint agency program that provides the funding for such a development and for this to be underpinned by an agreement by the operational community to support the migration and maintenance of techniques into the operational environment.

The proposed program would result in the development of a daily, quality-checked, comprehensive sea-ice product providing information on total and partial sea ice concentration, lead orientation, ice motion and ice thickness distribution. The product would be designed using techniques developed by the research community, implemented and maintained by the operational community, and archived at the National Snow and Ice Data Center. It would become a major long-term resource for the sea-ice community and would form the basis for future digital climatologies.

If this solicitation is successful, the U.S. science and operational sea-ice monitoring activities could be streamlined and rationalized, with the following concomitant benefits:

- ***effective use of the wide array of data*** available for Arctic monitoring, through the use of data assimilation techniques, which have been tried and tested in numerical weather prediction;
- ***enhanced funding base*** and ***strong program momentum*** through multi-agency involvement;
- ***improved return on research and operations investment*** through linking of technologies developed by each community and broadening of user base;
- ***availability of expertise*** from both the scientific community and the operational community;
- ***enhanced opportunities for product evaluation and validation***, through near real time availability of products and involvement of the operational community;
- a clear route for ***migration of science community techniques to the operational environment***;
- Provision of an ***overall strategy*** for Arctic sea-ice research.

3. Arctic-Wide Sea-Ice Product: The Current Situation

3.1 Processing and Archiving Infrastructure

For Arctic-wide sea-ice products, the scientific community is served by the National Snow and Ice Data Center (NSIDC), which provides an Arctic-wide SSM/I sea-ice product using the NASA Team algorithm (Steffen *et al.*, 1992). This product includes sea-ice concentration and, at lesser accuracy, multi-year ice concentration, and is provided with a frequency of once per day, but ordered from NSIDC on CD-ROM in blocks of data covering 3 months. For selected field experiments, near-real time passive microwave-derived ice concentrations can be retrieved from their FTP server. NSIDC also provides a range of other products, such as International Arctic Buoy Program (IABP) observations, data from campaigns (such as AIDJEX) and historical Arctic rawinsonde observations. Although NSIDC is the main point of contact within the scientific community for polar ice products, it does not at present generate or archive any assimilated Arctic-wide sea-ice product. As the focus of NSIDC is product archiving and dissemination, it would probably not wish to be regarded as a likely location for any operational data assimilation scheme.

The operational community is served by the National Ice Center (NIC). NIC incorporates information from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), which provides an SSM/I ice concentration product based on the CAL/VAL algorithm (Preller, 1985). FNMOC also uses this product to initialize the Polar Ice Prediction System (PIPS) Version 2.0 model of the Arctic, which provides forecasts of conditions over time intervals of between 24 and 120 hours. This model is a dynamic-thermodynamic sea-ice model coupled with the Cox ocean model (Preller, 1985). FNMOC is therefore already operating a rudimentary data assimilation scheme, although they give complete weight to the SSM/I data at the expense of the model predictions. At present FNMOC generates and disseminates these products, but do not archive them. The Shared Algorithm Research Panel (SARP) provides technical oversight to the FNMOC SSM/I products, and has a mandate to recommend changes to the algorithms installed there. This panel includes operational and scientific members and meets periodically to review whether operational changes need to be recommended to FNMOC.

Generation of these products by two distinct organizations represents an unncessary separation of processing efforts by the scientific and operational communities and the situation is illustrated in Figure 1 (compare with Figure 3 for the proposed scheme). Although there are two separate processing chains, there is no conflict of interest. NSIDC are primarily an archive and product dissemination facility and do not view themselves as an operational product generation facility. Their roles could therefore be entirely complementary in any operational data assimilation scheme.

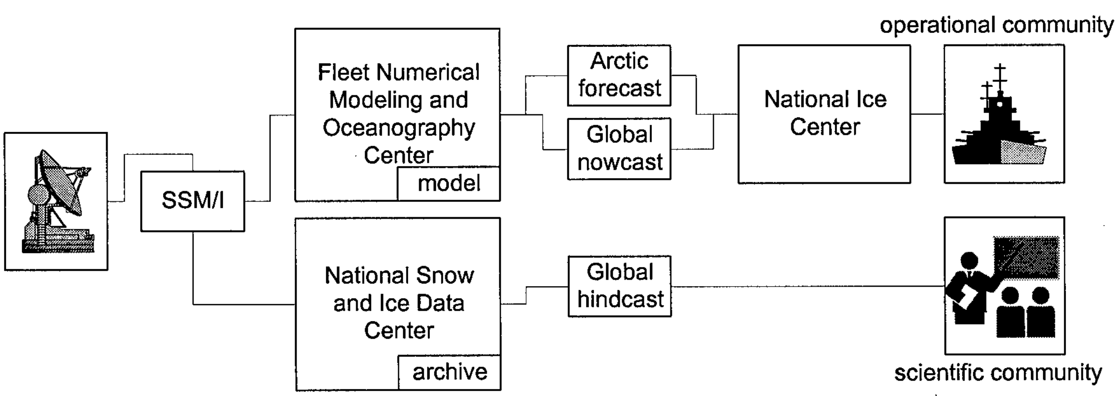

Figure 1. Illustration of the current scheme used to generate Arctic-wide sea-ice products.

3.2 Existing Development Strategy

The current development strategy for global-scale sea-ice products is based on single agency programs and lack of science-operations liaison that has the following disadvantages:

- Within the scientific community, projects tend to end with demonstrations of a product, with a relatively small likelihood of migration to an operational environment. Limitations on resources within the scientific community tend to result in very few geophysical products being made available on a routine basis to the scientific community. An exception was the GPS that was developed by JPL and based at the Alaska SAR Facility. This represented a relatively expensive development that had limited success in terms of demand from the user community.

- Funded projects, although rated highly within the review process and technically strong in many cases, do not necessarily fit into any large-scale strategy in terms of product development.

- Funding of operational developments can be based on an inadequate sampling of all available technologies. The operational community would benefit greatly from closer liaison with the scientific community and its sponsors in order to gain the benefit of their technical expertise and oversight.

In summary, there is no overall U.S. multi-agency strategy for development of sea-ice monitoring technology.

3.3 Existing Operational Sea-Ice Models

The only existing operational sea-ice model in the U.S. is the Polar Ice Prediction System (PIPS) version 2.0. This is an implementation of the Hibler dynamic-thermodynamic sea-ice model coupled with the Cox ocean model (Preller, 1985), which produces estimates of ice thickness, ice concentration and ice motion with forecasts up to 5 days. It is operated at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and it represents the culmination of significant ONR/Navy funding over the last 10-12 years. It covers the Arctic region, including most major marginal ice regions, and is updated using SSM/I-derived ice concentration data. The ice concentration data are used to replace the PIPS-derived ice concentration predictions on a daily basis and PIPS ice thickness and surface temperature observations are modified in a partially heuristic manner to make the parameters mutually consistent. The model is a visco-plastic model which supports continuum mechanics but does not support the development of fractures. The model therefore has a number of deficiencies in terms of its internal physics, the quality of the ocean model and also in terms of how it assimilates observations. This has prompted the Navy to support development of an improved sea-ice model (PIPS 3.0), the planning of which has only recently got underway.

3.4 Existing Wide Coverage Sea-Ice Observations

Satellite-based Arctic-wide products are currently based on the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) products, and in particular on retrieval of sea-ice concentrations. It is well recognized that these SSM/I algorithms are far from ideal, on their own, as the basis for an Arctic-wide sea-ice product. There are atmospheric effects which represent clutter in the signal; there are inaccuracies in ice concentration related to inherent variations in brightness temperatures associated with different surface types; there are problems distinguishing melt ponds and ice-free areas in summer, and there is geophysical cross-talk. While these products are interpreted manually in generating regional ice chart products (taking account of weather conditions and local climatology to "correct" product anomalies), anomalies are fed through automatically into the sea-ice model (PIPS 2.0). The model therefore reflects the biases of the SSM/I product. A current activity, which has oversight from SARP, is to add the NASA Team sea-ice product to the existing CAL/VAL sea-ice product. This represents an interim measure prior to a more extensive review of SSM/I algorithms, with Navy funding committed to

post-doctoral research support for this activity (based at NIC). Although this is a useful first step in improvement of the PIPS and SSM/I sea-ice products, it represents only a modest step forward and a more broadly-based approach to product development is needed to make substantial improvements in the overall product quality.

Routine ground observations are provided through the International Arctic Buoy Program, which provides synpotic-scale pressure, temperature and ice motion fields for the Arctic, and these are fed into a range of scientific and operational activities (including updating of PIPS). The program is funded through the National Ice Center and is managed by the Polar Science Center at the University of Washington.

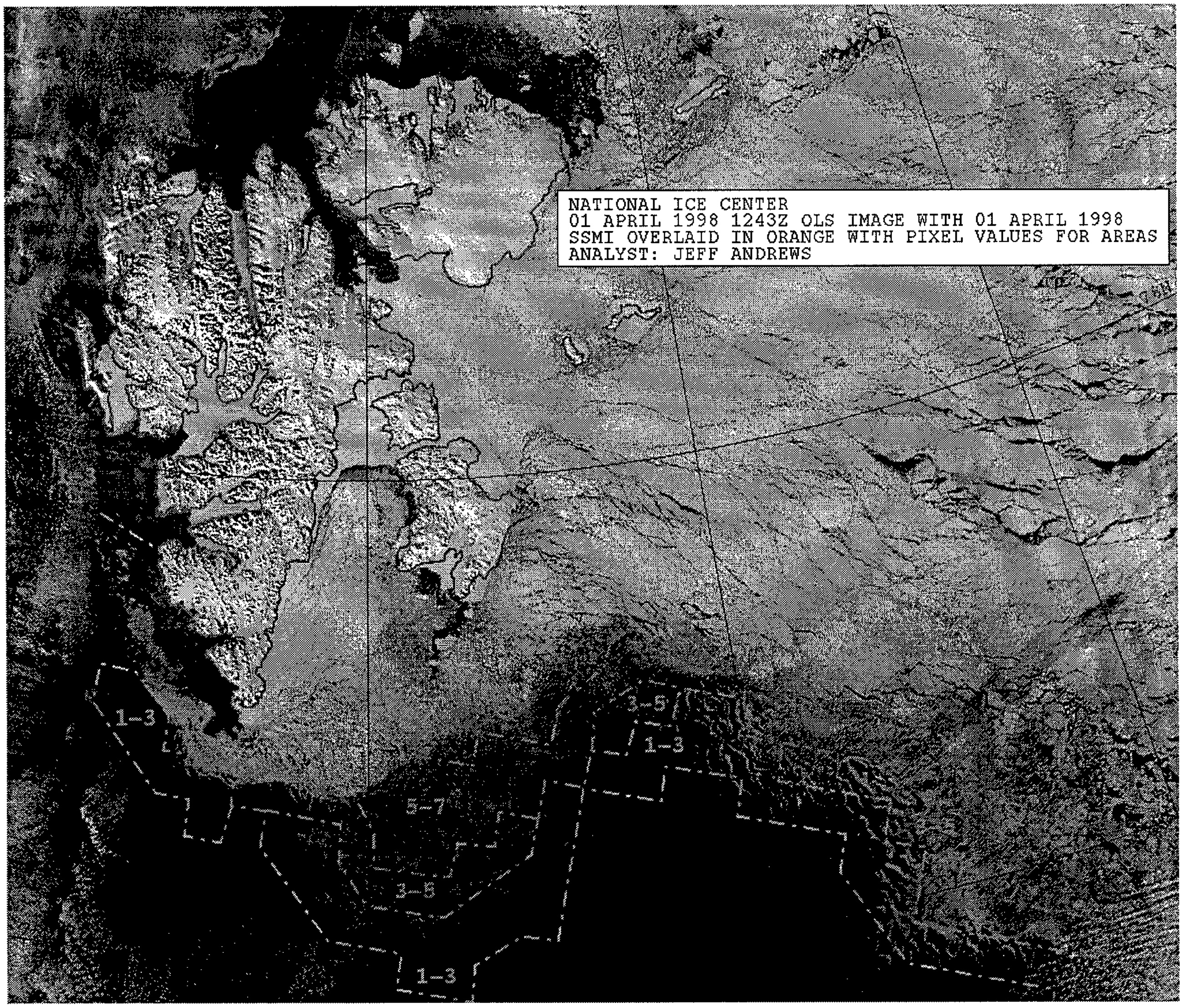

Figure 2. DMSP OLS image with overlying SSM/I-derived sea-ice concentration contours (in tenths) for the Svalbard region. The figure illustrates some of the limitations of SSM/I as the sole source of data for an Arctic-wide sea-ice product. Erroneously low ice concentrations can be seen where the ice surface is damp (e.g. north-north-east of 20E, 75N) and ice is missing in the SSM/I-derived contours just west of the southern tip of Spitzbergen (center-left of picture).

4. Arctic-Wide Sea-Ice Product: Requirements

4.1 Introduction

The implementation of a new product which serves both the operational and scientific community requires agreement on a set of requirements that meets the highest common denominator of both. In other words, it is imperative that the needs for both communities are met. Fortunately, the operational product requirements are met to large degree (but not entirely) by addressing the scientific requirements, with the exception of timeliness, and so the scientific community can take the lead in specifying the product requirements. Operational requirements, however, extend to cover issues related to implementation, such as the frequency with which product upgrades can be supported and algorithm specification requirements so operational requirements will necessarily drive the implementation process. In this section, the product requirements are addressed from the scientific and operational standpoints.

4.2 Scientific Requirements

4.2.1 Overview

Global sea-ice information is needed to address fundamental and critical questions concerning the nature of climate change. The requirements placed on the quality of the information are rigorous and reflect the difficult nature of these questions. The overall concern is the role of the polar regions in global climate, particularly in terms of heat and mass fluxes, but there are a wide range of specific questions which are being addressed by scientists. The long-term accumulation of knowledge of specific processes will contribute towards the gradual accumulation of an overall enhanced understanding of the role the polar environment in the climate system. A few of these questions are as follows:

- What is the relation of synoptic-scale circulation and meso-scale Arctic phenomena, such as ice edge eddies?
- What are the ice-land boundary conditions that influence so strongly the behavior of the ice pack in the shelf region where much of the oceanic heat loss occurs?
- What causes the equator-ward migration of polar vortices of the upper troposphere / lower stratosphere?
- What is the role of lead, polynya and new ice formation in ocean-atmosphere heat flux?
- What is the role of land distribution, large-scale ice and open water patterns and boundary layer processes on the formation and trajectory of polar lows?
- What are the interactions between the ice and open water in the marginal ice zone, and in particular what is the effect of oceanic process propagation into the ice?

The answers to these and other questions have a wide range of applicability to a number of practical issues beyond those related to the state of the climate system. These include the transportation of pollutants around the Arctic; statistical properties of ice cover for the planning of polar transportation and construction and military operations and exercises; improved weather forecasting and fisheries protection and management.

At present, these questions cannot be addressed adequately through the analysis of current sea-ice products, because of insufficient coverage, ambiguities in the data, poor resolution or inadequate model physics. All of these applications would benefit from a data assimilation scheme which is able to deal with many aspects of the Arctic system at once rather than a set of observing systems and models which each provide (in a controlled, algorithm sense) unrelated geophysical parameters.

4.2.2 Scientific Observation Requirements

Science requirements for sea-ice observations have been outlined in a number of reports and need not be discussed at length here. Table 1 summarizes the requirement based on a brief review of the literature.

Product	Parameters	Precision ideal (min.)	Accuracy ideal (min.)	Spatial Resolution ideal (min.)	Refresh
Ice Thickness	Histogram - thickness	n/a (n/a)	n/a (10%)	n/a (200 km)	168 hrs
	Histogram - area	n/a (n/a)	n/a (3%)	n/a (200 km)	168 hrs
Surface Type	Total (% cover)	n/a (5%)	3% (10%)	0.25 km (25 km)	24 hrs
	MY ice (% cover)	n/a (5%)	3% (10%)	0.25 km (25 km)	24 hrs
	FY ice (% cover)	n/a (5%)	3% (10%)	0.25 km (25 km)	24 hrs
Surface Properties	Temperature	0.1K (n/a)	0.5K (1.0K)	1 km (100 km)	168 hrs
	Wetness	n/a (n/a)	1% (n/a)	n/a (n/a)	24 hrs
	Melt pond coverage	n/a (n/a)	3% (n/a)	n/a (n/a)	24 hrs
	Snow cover depth	n/a (n/a)	n/a (5 cm)	0.25 km (25 km)	24 hrs
	Surface albedo	n/a (n/a)	n/a (0.05)	n/a (100 km)	12 hrs
Ice Motion	Gridded vectors	n/a (n/a)	1 cm/s (2 cm/s)	5 km (25 km)	12 hrs
	Deformation	n/a (n/a)	(0.5%)	n/a (25 km)	12 hrs

Table 1. Science requirements for monitoring sea-ice. This does not include non-ice products required for polar climate monitoring. Requirements are derived from Carsey (1992), Jacobowitz (1996), JSC Working Group (1992) and Rothrock (1997).

Table 1 defines the requirements from the point of view of the application. In other words, the requirements are not defined to be realistic in terms of current or future capabilities. It is important to have this information as an absolute reference against which to measure development of capabilities. Future goals will attempt to address the above requirements in a partial manner, gradually reducing the gap between capability and requirement. This gap may never be closed and some requirements may have higher priority than others (particularly in terms of operational needs), but data assimilation provides a framework within which to aim at this goal.

4.3 Operational Requirements

4.3.1 Overview

Operational requirements cover both products and implementation. As well as having a slightly different slant on product requirements, the operational community has specific requirements in terms of product timing and delay.

4.3.2 Operational Observation Requirements

The unclassified requirements of the operational community can be considered to include those of the scientific community, plus some additions (which will also be of interest to the scientific community). Table 2 identifies representative additional requirements.

Product	Parameters	Precision ideal (min.)	Accuracy ideal (min.)	Spatial Resolution ideal (min.)	Refresh
Ice Fractures / Leads	Modal orientation	n/a (n/a)	10 deg (20 deg)	n/a (10 km)	12 hrs
Directional Ambient Noise	Mean intensity as a function of freq.	n/a (n/a)	n/a (n/a)	n/a (n/a)	12 hrs

Table 2. Additional representative operational requirements for monitoring sea-ice, in addition to those of Table 1.

4.3.3 Product Timing

The products must be available on a daily basis for operational use and for building up long-term climatologies.

One of the advantages of data assimilation is that the products can be provided at a particular time of day, using the interpolation function of the procedure. This makes it possible to provide the product at particular times of each day for most efficient operational use (e.g. 00 GMT, 12 GMT, etc.). It is not expected that the science cmmunity will have strong views on this precise timing.

The products should be available for operational use within a period of 6 hours (preferable) or 12 hours (acceptable) of the time associated with the now-cast product. In practice, the extent to which the minimum requirement is exceeded will depend on a trade-off with product quality, as data assimilation can be used to extrapolate beyond the time associated with the last data source. The product could therefore be made applicable to the time at which the product is received (in effect, a forecast product). The delay, in this case, is zero hours, but the quality will be lower than a product that has a delay of 12 hours, but which is based on very recent data. In practice, the trade-off position will need to be determined through a program of evaluation and product tuning.

4.3.4 Implementation Requirements

The implementations must be sufficiently spaced apart to ensure that yearly costs are kept to reasonable levels for sponsors of the program. One implementation every two years is suggested as the target, with the first being two years after the start of the program. Where practical, implementations should be combined, which will require careful overall management of different projects.

The algorithm implementations must be under the control of representatives of the sponsoring agencies, plus representatives of the scientific and operational user communities. This is important to ensure that no single group feels disenfranchised within the process, although the rate at which the implementation

proceeds will depend on operational resources (with an analogous situation at the R&D phase of the process). As the program results in implementation of operational algorithms, the standards of algorithm specification and development are very important. The following standards are envisaged for support to the implementation team by the algorithm developers:

- Rigorous definition of algorithms in appropriate format in approved software design language;
- Modular design for algorithms;
- Specification of parameters and appropriate values;
- Provision of prototype software.

The product will need to be maintained and quality-controlled. The product will also need to be archived once this procedure is complete.

5. Arctic-Wide Sea-Ice Product: Proposed Implementation Plan

5.1 Overview of Proposed Infrastructure

The implementation plan involves a strategy for implementing the scheme (section 5.2) and proposed activities (section 5.3). ***The scheme described in this document is a straw-man plan.*** The proposed scheme is shown in Figure 3 (compare with Figure 1).

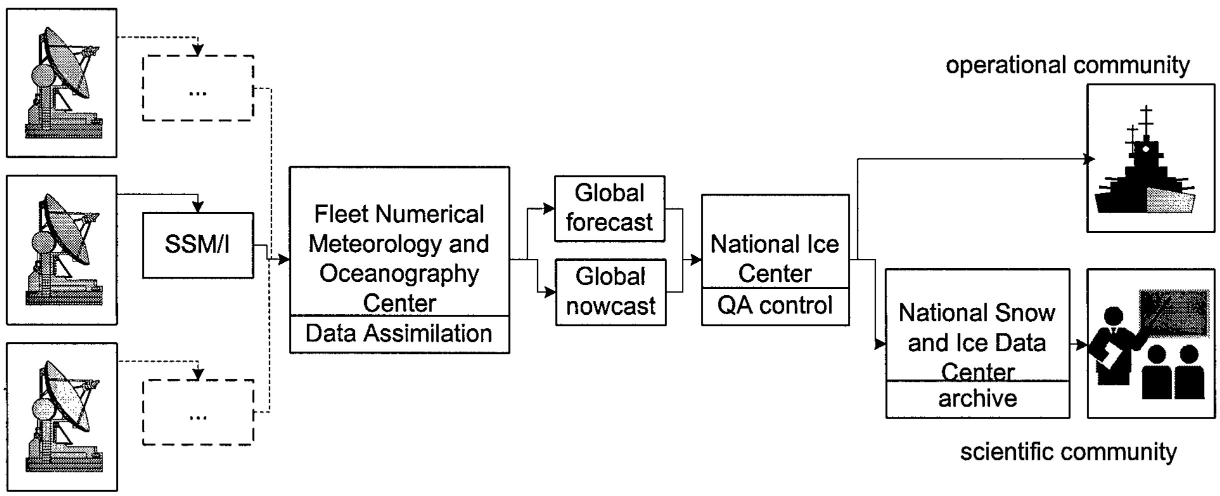

Figure 3. The proposed scheme for generation of a global ice product.

The data assimilation scheme will involve the use of a wide array of data, not all of it received from satellite. These data will be ingested in near real time at FNMOC where it is proposed that data assimilation scheme will be maintained. FNMOC is a designated microwave center of excellence and hosts the current Navy operational sea-ice model and so is a logical location for an operational data assimilation scheme. However, other centers could be used if required (such as NCEP). The data assimilation scheme will be used to generate a now-cast product and a forecast product. These will be provided to the National Ice Center (NIC) for quality checking and to support high resolution, near real-time, regional ice chart analysis before being disseminated to the NSIDC for access by scientists. The proposed roles are summarized in Table 3.

Agencies (NASA, ONR, NSF)	Fund R&D.
Navy, NOAA	Fund operational implementation.
FNMOC	Host, implement and maintain operational product.
NIC	Quality control of product.
NSIDC	Product archive center, science community I/F.
SARP	Overall coordination of program, recommendations to funding agencies.

Table 3. Proposed roles of organizations in program. All organizations listed currently hold SARP membership.

5.2 Proposed Implementation Strategy: An Operational Data Assimilation Scheme

5.1.1 Overview

It is proposed that the framework for development of an Arctic-wide sea-ice product be provided by data assimilation. This technique has been used within the meteorological (numerical weather prediction) community for some years and has clearly become part of the accepted methodology involved in weather forecasting and now-casting. Data assimilation provides the following benefits as an overall strategy for developing the sea-ice product:

- It provides a single, conceptual framework for development of products;
- It can make use of all available data and knowledge;
- It makes use of forward modeling rather than inverse modeling, which is conceptually simpler;
- It supports incremental advances in techniques;
- It can provide estimated errors along with the product;
- It supports filtering of diverse data;
- It supports optimal interpolation of data;
- It can provide products that are not directly observed.

Data assimilation is distinct from what is termed ***data fusion***. Data fusion is the combination of data sets to assist in resolving ambiguities inherent in a single data set, but data fusion does not imply the use of any physical model. In addition, it does not require the use of information across the temporal domain. An example of data fusion would be the use of multi-year ice concentration from synthetic aperture radar to constrain the NASA team algorithm estimate of sea-ice concentration from passive microwave data (Beaven *et al.*, 1996). ***Data assimilation***, on the other hand, is a broader methodology characterized by the features listed above, by definition including a combination of physical models, prior knowledge of a system and diverse data sets.

The origins of data assimilation techniques derive from the 1950s. Optimal interpolation techniques were developed first (see Eliassen, 1954, reprinted 1981) and by 1980 much of the data assimilation methodology for current numerical weather prediction was in place (see Bengtsson et al., 1981). Numerical weather prediction as an application of data assimilation is closely analogous to sea-ice monitoring and the data assimilation techniques developed by that community represent a valuable resource waiting to be exploited by the sea-ice monitoring community.

In this section, a brief review of the technique is given, based on the introduction to data assimilation provided by Errico (1997).

5.1.2 Data Assimilation: A Simple Case

Data assimilation is a methodology for ingesting diverse data sets and providing output which, in some "optimum" manner, both filters and interpolates from the input observations, and provides information on parameters not sampled directly by the observation network. The technique requires models for these three functions and information on error statistics of observations in order to arrive at a judgment regarding how to deal with the input data. Consider, as an example, an observation of a geophysical parameter and a model prediction of the parameter provided for the same location and time. One simple assimilation scheme is the maximum likelihood technique, which makes use of error statistics associated with the observation (O) and the prediction (P), such that:

$$E = P + (O-P)\{\sigma_p^2 / (\sigma_p^2 + \sigma_o^2)\} \quad (1)$$

where E is the estimated state and σ_p^2 and σ_o^2 represent the error variances associated with the predicted and observed states, respectively. It can be seen that if the prediction error is much larger than the observation error, then the estimate tends towards the observed state. If, conversely, the prediction error is much larger than the observation error, then the estimate tends towards the prediction. Thus, the quality of the estimate depends strongly on errors in both the predictions (which may be model-driven) and observations (which may be sensor-driven) and is basically a weighted mean of the two.

A range of estimation methods are available with which to determine how to make use of error statistics, beyond that of maximum likelihood. A Bayesian approach is conceptually useful, but rather impractical in the sense that it requires probability density error functions for all input data. A variational approach does not demand such complete error statistics but does demand some sort of prior knowledge of the data characteristics to support its use. A simple example of a variational approach would be to model the data as a linear function of some measurement parameter, so that the estimate can be obtained by a straight-line fit which allows interpolation to the measurement parameter of interest. A variational procedure can be extended to include other types of information through a weighting procedure (weighted sum of squares), based on relative error statistics. In the case where the error statistics are not distributed normally, there are estimation procedures more suited. An example is the case where the observations are contaminated by a relatively small number of points which have extremely large errors, thus skewing the distribution. The choice of estimation procedure therefore depends strongly on the depth of knowledge of error statistics (including co-variance of different parameters) and the extent to which the functional relationships of different parameters are known. The success of any of these techniques can be seen to depend critically on the accuracy with which error statistics are represented in the assimilation scheme, and specification of errors is therefore a most critical area of research for data assimilation.

5.1.3 Data Assimilation: More Sophisticated Approaches

As we move from a simple scalar system to a complex 4 dimensional system (with the temporal domain as the fourth dimension), the data assimilation scheme needs to become progressively more sophisticated. The difficulties of this more complicated scenario include the following:

- the observation and model points are not co-located (optimal interpolation required);
- the number of variables are large (scalar-to-vector generalization required);
- the observed parameters are different from the modeled parameters (physical model required).

Non co-location of points requires some sort of interpolation. The first generation of numerical weather prediction schemes, introduced after the second world war, were designed to deal with this requirement through interpolating observed data to a regular network of grid-points. Since then, the advent of non-synoptic data has made the procedure more complicated. Linear interpolation can make use of the radial distance to a measurement location plus some weight which reflects the quality of each point. There are also non-linear schemes, many of which are reviewed by Gustafsson (1981). With more than one variable, a multi-variate statistical interpolation scheme is required, and in their design these can make use of cross-correlations between the different variables. When the observed and modeled parameters are different, it is necessary to use physical modeling and a data assimilation scheme can typically include models relating observed parameters to model input parameters as well as a model for the general system behavior. An example of this would be radiative transfer modeling.

The Kalman filter represents one practical approach for assimilating data, and one which has been applied to assimilation of data in sea-ice studies (e.g. Thomas and Rothrock, 1993). The following summary of the Kalman filter approach is taken from articles by Thomas and Rothrock (1989 and 1993), Rothrock and Thomas (1992) and Thomas *et al.* (1996).

The discrete Kalman filter makes use of a state vector which describes the modeled system at time t(n). The state vector is a 1-D matrix describing the state of the system, as follows:

$$\mathbf{X} = (X_1, X_2, X_3, \ldots X_S)^T \qquad (2)$$

where s is the number of system conditions which are considered and $X_1 \ldots X_S$ are parameters which define the state of the system at time t(n) (s could, for example be defined as 4 and $X_1 \ldots X_S$ could be defined as partial ice type concentrations). Superscript T indicates the transpose of the matrix. The system evolves with time such that the state of the system at time t(n+1) is modeled as:

$$\mathbf{X}(n+1) = \Phi(n+1|n)\, \mathbf{X}(n) + \mathbf{S}(n+1) + \mathbf{V}(n+1) \qquad (3)$$

where the (s x s) transition matrix Φ describes the physical processes which determine the evolutionary form of the system; the (1 x s) matrix **S** is known as the in-homogeneous source term and the (s x 1) vector **V** describes the system noise (often assumed to be Gaussian white noise). The vector **V** can be thought of as physical processes that fail to be modeled, or are modeled imprecisely within the system. This "noise" is often further assumed to have the constraint that the co-variance matrix for **V** is limited to terms along the leading diagonal. A similar constraint is assumed to apply to measurement error matrix **W**, which is included in the relationship between the state of the system and the observed variables as a random, additive error term, as follows:

$$\mathbf{Z}(n) = \mathbf{H}(n)\, \mathbf{X}(n) + \mathbf{W}(n) \qquad (4)$$

where **Z** are the measurements, and **H** relates the observations to the state variables. For example, equation (4) could relate brightness temperatures from SSM/I to ice concentrations (Rothrock and Thomas, 1992).

In Rothrock and Thomas (1992), these equations are used in compiling both predictions and filtered results. The prediction, **X**(n+1|n), is based on the model and on data up to time t(n). The filtered estimate, **X**(n+1|n+1), is based on the difference between the prediction (**X**(n+1|n)) and the observation at time t(n+1). If the measurement errors are large, then the so-called gain is small and more weight is applied to the prediction, and vice versa. This procedure is then applied in a reverse form (stepping back in time). This latter procedure is a useful characteristic of data assimilation schemes.

The Kalman filter, as in any data assimilation scheme, can provide an estimate of the error in the estimated state of the system, as well as providing the estimate itself. However, the value of the technique depends sensitively on the assumptions and knowledge regarding error terms and the physical model. In general, the error associated with the model (**V**) is less easy to determine than the measurement error (**W**), as models are notoriously difficult to evaluate. Any invalid assumptions, or poor estimates of error, will serve to bias the output from the Kalman filter. Rothrock and Thomas (1992) show that the error in the simple case of a single variable reduces, in the case of the Kalman filter, to:

$$1/\sigma_T^2 = 1/(2R) + \mathrm{sqrt}\{1/(4(\sigma_O^2)^2) + 1/(\sigma_P^2\, \sigma_O^2)\} \qquad (5)$$

where σ_T^2 is the filter error covariance, σ_P^2 is the model error covariance and σ_O^2 is the measurement error covariance. It can be seen that if the measurement error is very small compared to the model error, then the filter error tends towards the measurement error. If the converse is true, then the model can reduce significantly the error from that attributable to the measurements (to $\{\sigma_O^2\, \mathrm{sqrt}(n)\}$, where n is the number of observations). Thus, the Kalman filter has similarities, in the limit, to the simple Maximum Likelihood scheme described earlier, and all data assimilation methods basically weight the use of data in inverse proportion to their relative errors.

5.1.4 Data Assimilation: Application to Sea-Ice Studies

Much important initial work in applying data assimilation techniques to sea-ice studies has been carried out by Rothrock and Thomas. Thomas and Rothrock (1989) incorporated both SMMR observations and buoy data into a sea-ice model using the discrete Kalman filter. This was an early example of data assimilation applied to the problem of realistic modeling of sea-ice behavior, building from earlier work by Thorndike (1988). Thomas and Rothrock specified the measurement model **H** include the two major principal components from the SMMR data (which describe 99% of the variation in the 10 channel SMMR data set), modified by surface temperatures determined from the buoy data (a linear regression model), and based also on season (see equations 2-4).

$$\mathbf{H} = \begin{matrix} [H_{1,OW} & H_{1,FY} & H_{1,SY} & H_{1,MY}] \\ [H_{2,OW} & H_{2,FY} & H_{2,SY} & H_{2,MY}] \end{matrix} \qquad (6)$$

where the first subscript indicates the principal component and the second subscript represents the surface partial ice type concentration. $H_{1,FY}$, for example, will vary as a function of season and surface temperature.

The physical model, as specified in the transition matrix Φ, is used to determine the system evolution between time-steps, as follows:

$$\Phi = \begin{matrix} [1-g & m_{FY} & 0 & 0] \\ [g & 1-a-m_{FY} & 0 & 0] \\ [0 & a & 1-a & 0] \\ [0 & 0 & a & 1] \end{matrix} \qquad (7)$$

where g is the ice growth parameter (1 during winter, 0 during summer, with open water assumed to take 1 day to freeze over), m is melt of ice (assumed to be during summer and to affect first-year ice only) and a is the again parameter (a=1 during freeze-up, 0 at other times). This transition matrix allows for such processes as changing first-year ice to multi-year at the end of summer. Thomas and Rothrock extend this model to include the case of melt-pond formation. Their approach is practical for the Arctic Ocean, where buoy data are available. However, they point to the difficulty of applying this approach to the Antarctic and the marginal ice regions in the northern hemisphere where data are sparse.

Thomas and Rothrock (1993) extended their work to apply data assimilation to the problem of determining the mass balance of the Arctic Ocean, using 7 years of buoy-derived ice motion fields and satellite passive microwave observations. They use 7 cells in the Arctic Ocean in order to account for regional variations in climatology and dynamics / thermodynamics. Their transition matrix accounts for ice melt and growth, as before. Their transition matrix is extended, however, to account for ice convergence (which will reduce the concentration of first-year ice) and general advection based on buoy data. The advection and convergence observations are determined via an optimal interpolation procedure, weighted between the buoy observations and free drift based on geostrophic winds (modified by a seasonal drag factor and turning angle). Where the error in the buoy interpolation is estimated to be large, the free drift estimates are used. Thomas and Rothrock used this technique to evaluate regional differences in climatology and dynamics and significant sources of error. SSM/I-derived ice concentrations were identified as a major source of uncertainty in interpretation of the results. The same technique was applied further by Thomas et al. (1996), who looked at ice thickness distributions across the Arctic.

5.2 Proposed Activities

5.2.1 Overview

Research activities in support of the proposed program will not consist entirely of new initiatives. Much existing and past work has contributed to the development of techniques that are relevant, although many of these may need to be modified or extended to make them applicable. These, and areas of research which are more completely lacking, will require development funds. In this section, a review of the application of data assimilation techniques to sea-ice monitoring is provided, along with recommended development plan for future work.

5.2.2 An Improved Coupled Ocean-Ice Model

The existing operational ice model, PIPS 2.0, has several weaknesses that would severely limit its value as a potential cornerstone of an operational data assimilation scheme. In order to support data assimilation and provide output that more closely meets the requirements listed in section 4, the model needs to undergo a program of upgrade in several key areas. Before addressing these, it is worth summarizing the history of the Navy ice modeling program.

The U.S. operational sea-ice modeling program is relatively new, and is based on modeling design work carried out in the late 1970s. The operational community, with a requirement for short-term forecasting of sea-ice conditions, recognized the need for an operational sea-ice model in the 1980s and also recognized that this would need to be constantly initialized and updated by observations. The model, run at FNMOC and called the Polar Ice Prediction System (PIPS), is an implementation of the Hibler dynamic-thermodynamic sea-ice model coupled with the Cox ocean model (Preller, 1985), which produces estimates of ice thickness, ice concentration and ice motion with forecasts up to 5 days.

The PIPS model uses daily information on ocean currents, oceanic heat flux, incoming solar radiation, sensible heat flux, surface air temperatures, geostrophic wind stresses and ice concentration. The oceanic variables are based on monthly mean values derived from the Cox ocean model (Hibler and Bryan, 1987) and the ocean model has 15 levels which increase in thickness with depth (the top layer, 30 m in thickness, is the mixed layer). The grid cells have a size of 17-33 km (depending on latitude). The ice and ocean models in the current version of PIPS (2.0) are coupled through exchange of salinity, heat and momentum (wind-ice-current stresses). The model is initialized using climatological temperature and salinity data and is initialized with an "average" ice thickness and ice concentration for winter. The model also includes freshwater input from eight major rivers that flow into the Arctic. Daily forcing, in terms of heat fluxes and surface winds, is provided by the Navy Operational Global Atmospheric Prediction System (NOGAPS).

PIPS 2.0 is updated on a daily basis with SSM/I ice concentrations derived from the CAL/VAL ice concentration algorithm (Preller, 1985). The assimilation procedure is carried out by replacing the modeled ice concentration estimates by the SSM/I-derived estimates. This procedure results in some areas being assigned an increased ice concentration and some areas being assigned a decrease in ice concentration. The ice thickness field is made consistent with the replacement ice concentration field, in a partially heuristic manner such that adjusted ice thicknesses are changed in proportion to the change in ice concentration. The surface temperature fields are likewise modified to ensure that areas of increased ice concentration are set at freezing point and areas of reduced concentration are set above freezing point (to avoid immediate refreezing). Thus, while SSM/I observations are assimilated into the PIPS 2.0 coupled ice-ocean model, the assimilation procedure is crude and, effectively, applies full weight to the SSM/I observations at the expense of the model predictions.

The ice concentrations which are assimilated into PIPS are obtained using the CAL/VAL algorithm, which is known to be weak in some important respects (such as in over-estimating ice concentration in

winter pack ice). These weaknesses are fed into the ice model, with no weighting procedure to offset any algorithm bias. Ice concentrations derived from NIC ice charts have less bias, as they are based on a wide variety of data and expert knowledge of local climatology and weather patterns. A comparison of the model output generated using initialization with the daily SSM/I ice concentrations against the weekly NIC ice charts demonstrates that the improved accuracy and spatial resolution afforded by the NIC ice charts is more than offset by their poor temporal resolution. However, improvement of the PIPS 2.0 output is envisaged, by replacing the CAL/VAL algorithm with the NASA Team algorithm in the short term. A more thorough evaluation and improvement of the SSM/I ice concentration algorithm is planned in the medium term.

The features requiring upgrade are as follows:

- Replacement of climatological ocean input by a more accurate ocean model which assimilates observational data, plus more precision in terms of vertical resolution in the ocean model (especially better treatment of the mixing layer), and improved bathymetric spatial resolution. Also, replacement of the Bryan-Cox primitive equation by a free surface formulation.

- Replacement of the crude, and partially heuristic, data assimilation methodology. A physical model which supports data assimilation should be implemented within the framework of a data assimilation schema, where observational inputs do not routinely replace model predictions, but are weighted in their use, based on some measure of their accuracy. A simple example would be weighting of SSM/I ice concentration data based on weather filter values.

- Replacement of continuum mechanics (based on viscous-plastic rheology), which cannot support fractures, by an anisotropic, elastic-viscous-plastic rheology with fracture mechanics.

- Improvement of grid spacing to about 10 km.

- Addition of ambient noise prediction module, for operational requirements.

- Assimilation of a wider array of data, including (initially) SSM/I, synoptic winds and heat flux, and extending to include radiation (COAMPS), ice motion vectors from the IABP and 85 GHz SSM/I, and eventually ice surface parameters from QUICKSCAT and MODIS.

- More efficient implementation using distributed shared memory architecture. This type of consideration is important in order to support the intensive computational demands of a data assimilation scheme.

These improvements are already being initiated through Navy investment, with a planned PIPS 3.0 implementation.

5.2.3 Assimilation of Ice Concentration

Passive microwave observations are, at present, the primary source of data on global-scale sea-ice coverage. The passive microwave brightness temperatures are applied to an inverse modeling scheme, but all these schemes contain major biases, to varying degrees. These include the following:

- Errors resulting from natural variations in brightness temperatures associated with reference areas of open water and sea-ice types.

- Geophysical cross-talk errors. In the case of sea ice concentration estimation, for example, a manifestation of this error is sea-ice concentration being correlated, erroneously, with surface temperature.

- Surface melt - related errors, which cause most SSM/I algorithms to under-estimate ice concentration. Errors in ice concentration tend to double to 10-20% for algorithms (Steffen et al, 1992) during summer and the errors are systematic. Russian drift stations show that, at times, as much as 45% of the ice may be covered by melt ponds in mid July (Thomas, 1993), and this will be reflected in lower estimates of ice concentration from passive microwave data.

- Errors related to the presence of new and young ice types, which are not explicitly accounted for in the operational SSM/I ice concentration algorithm. In freeze-up conditions, there will always be a tendency for ice concentration to be under-estimated as a result of this effect, as the emissivity of new ice can approach that of open water (0.45). Steffen and Schweiger (1991) found that the presence of nilas and young ice could create an under-estimate of ice concentrations from SSM/I of 9% (with global tiepoints) and 4% (with local tiepoints), using the NASA Team algorithm.

- Atmospheric transmission errors are caused by the susceptibility of passive microwave sensors to cloud liquid water and water vapor, integrated along the path length of the radiation. These errors are currently impossible to predict reliably and so SSM/I algorithms make use of fairly crude weather filters to reject ice concentrations over open ocean.

In a data assimilation scheme, this inverse modeling approach would be replaced by a forward modeling scheme, in which the brightness temperatures are predicted based on estimated surface (and maybe atmospheric) conditions and a forward modeling scheme could be developed which attempts to reduce the errors listed above. Forward modeling starts with a specification of the surface (e.g. partial ice concentrations) and attempts to predict the observation parameter (e.g. brightness temperature). Inverse algorithms attempt the reverse.

Steffen and Schweiger (1991) have found that the use of local tie-points can (in some circumstances) halve the r.m.s. difference in ice concentrations derived from SSM/I and visible / infra-red sensors (AVHRR and Landsat), and the use of local tie-points is particularly beneficial in the Arctic, where there are marked regional differences in ice climatology. Routine incorporation of local tiepoints in a forward modeling procedure (using other data sources) would improve the estimation procedure considerably. Some of the atmospheric artifacts present within passive microwave observations could be treated more appropriately by applying a weather filter that weights the use of the SSM/I data in an assimilation scheme, rather than replaces the observations (as conventionally happens). Geophysical cross-talk is a characteristic of inverse modeling which would be avoided by forward modeling. Surface melt-related errors could also be addressed through the assimilation procedure. During summer, greater weight could be placed on the model predictions than on the observations, to reduce the impact of "erroneous" low, summer ice concentrations suggested by the passive microwave data (modifying the gain factor referred to in section 5.2.1). The problem of new ice has received some recent attention. A thin ice formulation of the NASA team algorithm has recently been published, for example, and could be investigated as a potential addition to the existing source of information (Cavalieri, 1994). Many of these issues are planned to be addressed through Navy funding of an NIC post-doctoral research position.

Perhaps a more productive long-term approach to improving the assimilation of ice concentration would be to assimilate other data besides SSM/I. One such data source is synthetic aperture radar (SAR). SAR has only recently become available on an operational basis through the Canadian RADARSAT program (previous SAR sensors had coverage which weas too limited to be operationally useful). Follow-on missions include the European Space Agency ENVISAT platform and RADARSAT II. Wide swath modes of these sensors provide extensive coverage and Lagrangian tracking (using the RGPS) has been used to map discrete fracture zones that have been shown for the first time to extend across wide regions of the Arctic. Automated processing of these data has proved more difficult and to date these data have not been used operationally in any automated fashion. Even ice tracking, the most mature SAR technique, includes a manual procedure. However, SAR is the focus of intensive efforts to develop automated

products and the advent of dual polarization SAR data ENVISAT may well result in development of a successful ice classification algorithm, although wide coverage dual polarization data is not planned to be available within the current generation of spaceborne SAR sensors. Thus SAR has some potential, but a number of limitations related to data coverage, processing demands and ambiguities.

In contrast, scatterometer data offers considerable promise for wide coverage observations of sea-ice. QUICKSCAT is planned for launch later this year and these data will be available in near real time. Scatterometer data have a major advantage over SSM/I data in being insensitive to atmospheric artifacts, and demonstrations of the potential of scatterometer data for sea-ice monitoring have proved persuasive using the ERS-1 scatterometer and NSCAT, on-board ADEOS. The nominal spatial resolution is somewhat lower than that of SSM/I, but resolution enhancement techniques can provide comparable resolution. Assimilation of QUICKSCAT data should be a key objective of a data assimilation scheme.

MODIS too has potential, given the possibility of an effective ice/cloud filter. If this proves successful, then MODIS could provide an ice/water classification product.

It can therefore be appreciated that, since the advent of SSM/I, there has been a major growth in the range and operational value of data-sets which are now available to the sea-ice community. When combined with sensors expected to be available on an operational basis within the next 2-3 years, it becomes clear that reliance on SSM/I alone for routine Arctic-wide sea-ice monitoring becomes indefensible, particularly given its known weaknesses (see Appendix A). As a result, it is important to plan now for development of an operational scheme that will include at least QUICKSCAT and possibly also MODIS and wide-swath SAR sensors.

5.2.4 Assimilation of Ice Motion Vectors

The International Arctic Buoy Program has been providing observation across the Arctic since 1979. Although these buoys are used as an important source of information for modeling of the Arctic through providing source data for gridded temperature / wind fields (which "drive" PIPS 2.0), the buoy motion information is not used in PIPS 2.0. The motion vectors provide sparse spatial distribution but high temporal resolution and use of these data could be crucial to realistic modeling of ice dynamics in the Arctic. At any one time, there are an average of about 15 buoys in service and these provide data in near real time. This represents a valuable resource for a data assimilation scheme.

Ice motion fields from satellite data complement ice motion data from buoys (by providing high spatial resolution, but relatively lower temporal resolution) and ice motion vectors represent perhaps the most mature sea-ice product to be derived from satellites. These were first derived manually in the early 1980s using Seasat SAR data. Later, the technique was partially and fully automated in various forms, but the most successful of these algorithms has been based on a hierarchical cross-correlation technique developed by Fily and Rothrock (1987). A range of other techniques have been designed, with the aim of being applied to the marginal ice zones where the Fily and Rothrock technique is less successful (e.g. Peddada and Chang, 1996). However, the Fily and Rothrock technique has proved to be remarkably robust, and has formed the basis for the design of the Geophysical Processor System (GPS) at ASF; the new Radarsat GPS (RGPS) system currently being evaluated prior to installation at ASF, as well as the basis for the tracker components of commercial sea-ice packages. These motion vectors are typically derived for a period of up to a "few" days, representing the period of revisit of satellite sensors that give reasonable or good coverage of the surface at polar latitudes. The Fily and Rothrock technique has been applied successfully to SSM/I 85 GHz data (where the spatial resolution is better than other passive microwave channels), AVHRR data and SAR data. The algorithm that is used varies from implementation to implementation, in details of filtering, correlation window size, etc., but remains relatively generic. The Lagrangian approach of the RGPS is potentially useful for an operational scheme, but the manual procedure associated with correcting "erroneous" tie-points would need to be automated and the processing burden of using basin-wide RADARSAT data in near real time is considerable. A similar

scheme based instead on SSM/I 85 GHz data (perhaps controlled using buoy observations) would be worth investigating.

In order to make use of these ice motion data two main developments are required. The most important was mentioned earlier and is a conceptual issue related to how to ingest ice motion information into a dynamic ice model in such a way as to influence the behavior of the model in a realistic manner. A crude, instantaneous forcing of the model upon each ingestion of ice vectors, as has been tried with PIPS, is undesirable. This problem is non-trivial and requires some careful consideration.

The second required development is to provide an ice tracker which is generic enough to operate on any data which meets criteria of revisit time and sampling capability. In principle, a cross-correlation tracker could be designed as a batch processor to operate on image pairs which are of a certain type (Radarsat, 85GHz SSM/I, AVHRR), cover the same area and were recorded within a certain number of days of each other. Any manual element of an algorithm would need to be removed and the operating parameters associated with the algorithm would need to be tuned for each sensor. The constant supply of motion vectors from IABP buoy data and from a range of satellite sensors would improve considerably the gross behavior of the model. Initially, it would make sense to focus efforts on ingestion of 85 GHz SSM/I ice motion and IABP-derived motion. At a later date, motion vectors can be added from SAR and AVHRR and any other satellite sensors if the product quality is good enough and the algorithm can be fully automated.

5.2.5 Assimilation of Radiative Flux

The potential exists to obtain radiative flux from space-borne sensors. The benefits of incorporating this information into a data assimilation scheme are considerable, as these fluxes are essential to any realistic modeling of sea-ice thermodynamics. According to one study, a 10% change in the long-wave radiative flux can change the computed mean ice mass by some 36%. Radiative flux would also assist in the forward modeling of data from other spaceborne sensors, particularly SSM/I.

Key *et al.* (1996) focused attention onto work preparatory to the assimilation of radiative fluxes. Whilst existing climatologies may be used to prescribe fluxes, modified perhaps using relatively recent satellite-based observations of cloud and surface conditions, parameterizations of the long-wave and short-wave radiative fluxes are more appropriate for a data assimilation scheme where short term variability in fluxes are important to consider. In these parameterizations, the short-wave flux is usually taken as a function of the solar constant and zenith angle, with parameters modified to be appropriate for the polar regions. In some cases, near surface vapor pressure is used as an input variable. When cloud is present, the short-wave flux is often multiplied by a simple cloud factor, which can be given as a function of latitude and may be non-linear as a function of cloud cover, to account for the influence of low cloud (which affects short-wave radiation the most and tends to increase in cover as high cloud cover increases). The most accurate parameterization for short-wave radiative flux was judged by Key et al. to be one which included surface albedo and cloud optical depth. The long-wave radiative flux is taken to be a function (to the fourth power) of near surface air temperature. When cloud is present, the fractional cover needs to be taken into account. Some parameterizations are more sophisticated than others. An example is a parameterization of long-wave radiative flux which accounts for cloud base temperature, which is not readily observed and so is of limited utility for a data assimilation scheme. Key et al. identify parameterizations of radiative flux which appear to be most successful in comparison with in situ measurements.

Some workers, including Key, have already demonstrated that radiative flux can be derived from AVHRR. The challenge with AVHRR is to derive this information in an operational manner. The launch of MODIS in 1998 should lead to a significant enhancement in the availability of routine observations related to radiative flux in the polar regions. Products that are planned to be obtained routinely, in near real time, include surface albedo, cloud fraction and ice surface temperature. MODIS could, potentially,

advance sea-ice remote sensing significantly, although at the present time it is not clear how successful these products will be.

A clear objective should of a data assimilation scheme should be to make use of MODIS in supporting development of an improved ice growth and decay model within PIPS 2.0. These radiative flux observations should also be used to develop a reliable forward modeling algorithm for SSM/I data.

5.2.6 Assimilation of Sea-Ice Thickness

Ice thickness is perhaps the parameter of greatest interest to the scientific community, as it provides the key (along with ice concentration) to energy exchange between the ocean and atmosphere and yet has proved to be the most difficult parameter to derive through the use of measuring tools alone. The best hope for derivation of this parameter with significant coverage appears to lie in the application of a data assimilation approach. Although the methodology behind the Radarsat Geophysical Processor System appears to offer some potential for retrieval of ice thickness, it would depend on near real time provision of these products to FNMOC. Such a possibility appears to be remote.

Ice thickness is currently provided as output from the PIPS 2.0 model, but it is not constrained except through some relatively crude climatologically-based rules. There is considerable room for improvement of model output by incorporation of ice thickness observations, even if these are relatively sparse. The benefits of implementing such a scheme are considerable in terms of the accuracy with which energy balance calculations may be carried out for the Arctic, and hence the extent to which the role of the Arctic in global climate is established.

Assimilation of ice thickness data for the region of the SHEBA test site, again using the Kalman filter, is the subject of a current study led by R. Lindsay (personal communication). This represents a good test case for the assimilation of diverse data sets, including linear ice thickness tracks from submarine, point observations (moored buoys), 2D spatial data (RGPS-derived ice thickness histograms) and other data. A physical dynamic-thermodynamic model, which uses SHEBA test site observations of radiative flux and other parameters, is used to evolve the system. This project should result in an improved model for ice growth and decay based on radiative flux, which should be useful for PIPS 2.0 and other thermodynamic sea-ice models and could be tied in to work carried out on incorporating MODIS observations in a data assimilation scheme.

The SHEBA ice thickness assimilation project could be used as the basis for the design of an operational assimilation scheme, although it would need to be distinct from the existing SHEBA ice thickness assimilation scheme by relying solely on data that are available in near real time. Unfortunately, many of the data sources used in the SHEBA ice thickness assimilation project are unlikely to be available in near real time, and so assimilation of ice thickness observations is unlikely to be possible in the near future. Instead, the best hope seems to be to improve constraint on the ice thickness model in PIPS through assimilation of radiative flux and improved assimilation of ice concentration and ice motion.

6. Summary of Recommendations

In summary the following recommendations are made:

- NASA should undertake to lead a program of Arctic-wide sea-ice product development that would be coordinated with the operational community through ONR. This program should ideally be a joint agency program involving NSF and NOAA;

- ONR should undertake to liaise with NASA to ensure that the planned PIPS 3.0 model development is consistent with NASA plans and meets scientific requirements.

- The U.S. Navy, through FNMOC, should undertake to support the implementation of a data assimilation scheme, subject to successful demonstration of techniques.

- A working group, oversight committee, or some other formal liaison mechanism should be established to manage the program.

7. References

[1] Beaven, S.G., Gogineni, S. and Carsey, F.D., 1996, "Fusion of satellite active and passive microwave data for sea-ice type concentration estimates", IEEE Trans. Geosci. Rem. Sens., Vol 34, No. 5, pp. 1172-1183.

[2] Bengtsson, L., Ghil, M. and Kallen, E. (eds.), 1981, "Dynamic Meteorology: data assimilation methods", publ. Springer-Verlag (series: Applied Mathematical Sciences Vol. 36).

[3] Carsey, F.D. (ed.), 1992, "Microwave Remote Sensing of Sea-Ice", American Geophysical Union, Monograph No. 68.

[4] Cavalieri, D., "A microwave technique for mapping thin sea-ice", Jnl. Geophys. Res., vol. 99, no. C6, pp. 12,561-12,572, 1994.

[5] Comiso, J. and Kwok, R., 1996, "Surface and radiative characteristics of the summer Arctic sea-ice cover from multi-sensor satellite observations", Jnl. Geophys. Res., Vol. 101, 28,397-28416, Dec. 15.

[6] Daley, R., 1997, "Atmospheric data assimilation", in "Data assimilation in meteorology and oceanography", Proc. 2nd symp. on "Assimilation of observations in meteorology and oceanography", Met. Soc. Japan, 13-17 March, 1995, Tokyo, Japan, pp. 209-219.

[7] Eliassen, A., 1981, "Provisional report on calculation of spatial covariance and auto-correlation of the pressure field", in Bengtsson *et al.* (1981), pp. 319-330.

[8] Errico, R., 1997, "Introduction to data assimilation", presented at workshop on "Sea Ice Monitoring into the next Millenium: Workshop to evaluate new approaches to sea ice observation", Boulder, Colorado, 3-5 December 1997.

[9] Fily, M. and Rothrock, D.A., 1987, "Sea ice tracking by nested correlations", IEEE Tran. Geosci. Rem. Sens., Vol. GRS-25, pp. 570-580.

[10] Ghil, M. and Malanotte-Rizzoli, P., 1991, "Data assimilation in meteorology and oceanography", Adv. Geophysics, Vol. 33, pp. 141- 266.

[11] Gustafsson, N., 1981, "A review of methods for objective analysis", in Bengtsson *et al.* (1981), pp. 17-76.

[12] Hibler, W.D., 1979, "A dynamic-thermodynamic sea-ice model", Jnl. Phys. Oceanography, Vol. 9, pp. 815-846.

[13] Hibler, W.D., 1980, "Modeling a variable thickness sea-ice cover", Monthly Weather Review, Vol. 108, pp. 1943-1973.

[14] Hibler, W.D. and Bryan, K., 1987, "A diagnostic ice-ocean model", Jnl. Phys. Oceanogr., Vol. 17, pp. 987-1015.

[15] Jacobowitz, H. (ed.), 1996, "Climate measurement requirements for the National Polar-orbiting Operational Environmental Satellite System", Workshop Report, University of Maryland, College Park, 27-29 February, 1997, NOAA Contract Report, No. NA57GPO576.

[16] JSC Working Group, 1992, "Scientific Concept of the Arctic Climate System Study (ACSYS)", WMO/TD No. 486.

[17] Key, J.R., 1995, "The cloud and surface parameter retrieval (CASPR) system for polar AVHRR: user's guide", version 1.0A, Cooperative Institute for Research in Environmental Sciences report, University of Colorado, 71 pp..

[18] Key, J.R., Silcox, R.A. and Stone, R.S., 1996, "Evaluation of surface radiative flux parameterizations for use in sea-ice models", Jnl. Geophys. Res., Vol. 101, C2, pp. 3,839-3,849.

[19] Maslanik, J.A. and Maybee, H., 1994, "Assimilating remotely-sensed data into a dynamic-thermodynamic sea-ice model", Proc. IGARSS 1994, Pasadena, CA, pp. 1306-1308.

[20] Peddada, S. and Chang. T., 1996, "Bootstrap confidence region estimation of the motion of rigid bodies", Jnl. of American Stat. Assoc., Vol. 91, No. 433, pp. 231-241.

[21] Preller, R.H., 1985, "The NORDA/FNOC Polar Ice Prediction System (PIPS) - Arctic: A technical description", NORDA Report 108, 60 pp., Naval Ocean Research and Development Act., NSTL, Miss.

[22] Rothrock, D.A., 1997, Table on Polar Sea Ice Data Requirements - v.5.3, 27 May 1996, in Weaver, R., "Data Sets for Sea Ice Monitoring", presented at workshop on "Sea Ice Monitoring into the next Millenium: Workshop to evaluate new approaches to sea ice observation", Boulder, Colorado, 3-5 December 1997.

[23] Rothrock, D.A. and Thomas, D.R., 1992, "Ice modeling and data assimilation with the Kalman Smoother", in Carsey, F.D. (ed.) "Microwave remote sensing of sea-ice", publ. American Geophysical Union, pp. 405-418.

[24] Steffen, K., Key, J., Cavalieri, D., Comiso, J., Gloersen, P., St. Germain, K. and Rubinstein, I., 1992, "The estimation of geophysical parameters using passive microwave algorithms", in Carsey, F (ed.) "Microwave Remote Sensing of Sea Ice", Geophysical Monograph 68, AGU, 1992.

[25] Steffen, K., Schweiger, A., "NASA team Algorithm for sea ice concentration retrieval from Defense Meteorological Satellite Program Microwave Imager: comparison with Landsat Satellite Imagery", Jnl. Geophys. Res., 96, 21,971-21,987, 1991.

[26] Talagrand, O., 1997, "Assimilation of observations: an introduction", Proc. 2nd symp. on "Assimilation of observations in meteorology and oceanography", Met. Soc. Japan, 13-17 March, 1995, Tokyo, Japan, pp. 209-219.

[27] Thomas, D., "Arctic sea-ice signatures for passive microwave algorithms", Jnl. Geophys. Res., 98, C6, pp. 10,037-10,052, 1993.

[28] Thomas, D., Martin, S., Rothrock, D.A. and Steele, M., 1996, "Assimilating satellite concentration data into an Arctic sea-ice mass balance model, 1979-85", Jnl. Geophys. Res., C9, pp. 20849-20,868.

[29] Thomas, D.R. and Rothrock, D.A., 1989, "Blending sequential scanning multi-channel microwave radiometer and buoy data into a sea ice model", Jnl. Geophys. Res., Vol. 94, C8, pp. 10,907-10,920.

[30] Thomas, D.R. and Rothrock, D.A., 1993, "The Arctic Ocean Ice Balance: A Kalman Smoother Estimate", Jnl. Geophys. Res., Vol. 98, C6, pp. 10,053-10,067.

[31] Thorndike, A.S., 1988, "A naïve zero-dimensional sea-ice model", Jnl. Geophys. Res., Vol. 93, C5, pp. 5,093 - 5,099.

[32] Weaver, R., (ed.), 1997, White Paper on "Sea ice monitoring into the next millenium: new approaches to sea ice observation", Boulder, Colorado, 3-5 December 1997.

8. Glossary

AMSR	Advanced Microwave Scanning Radiometer
ASF	Alaska SAR Facility
ASL	Arctic Submarine Laboratory
AVHRR	Advanced, Very High Resolution Radiometer
AVS	Application Visualization System
CCRS	Canadian Centre for Remote Sensing
CIS	Canadian Ice Service
DAAC	Data Active Archive Center
DERA	Defence Evaluation and Research Agency (UK)
DMI	Danish Meteorological Institute
ERS	ESA Earth Resources Satellite
ESA	European Space Agency
ESIP	Environmental Science Information Partner
FNMOC	Fleet Numerical Meteorology and Oceanography Center
IIP	International Ice Patrol
JPL	Jet Propulsion Laboratory
KU	University of Kansas
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
NDRE	Norwegian Defense Research Establishment
NERSC	Nansen Environmental Remote Sensing Centre, Norway
NESDIS	National Environmental Satellite, Data and Information Service
NIC	National Ice Center
NOAA	National Oceanic and Atmospheric Agency
NOW	North Open Water (north Baffin Bay)
NPGS	Naval Postgraduate School, Monterey
NRL	Naval Research Laboratory
NSCAT	Japanese ADEOS satellite wind scatterometer
NSIDC	National Snow and Ice Data Center
NSIPS	Navy Satellite Image Processing System
NWS	National Weather Service
OOAR	Office of Oceanic and Atmospheric Research
OLS	Operational Linescan System
ONR	Office of Naval Research
ORA	Office of Research Applications
PIPS	Polar Ice Prediction System
RGPS	RADARSAT Geophysical Processor System
SAR	Synthetic Aperture Radar
SHEBA	Surface Heat and Energy Balance of the Arctic (campaign)
SSC	Stennis Space Center
SSM/I	Special Sensor Microwave Imager
USARC	United States Arctic Research Commission
USCG	United States Coast Guard
UW	University of Washington

Appendix A. List of anticipated operational sensors

Satellite	Sensor	Frequency band	Spatial Res'n meters	Country	Launch date	Anticipated operational status
TIROS	AVHRR	VIS/IR	1100 - 4000	USA	past	operational
DMSP	SSM/I SSMIS	MW MW	12,500 - 25,000 12,500 - 25,000?	USA	past, 1999 2001	operational
DMSP	OLS	VIS/IR	550 - 2700	USA	past	operational
NPOESS	follow-on to DMSP and NOAA satellites			USA	2008	operational
GOES-N	VAS	VIS/IR	4000	USA	past?	operational[1]
RADARSAT	SAR	MW	10 - 150	CAN	past, 2000	operational
EOS	MODIS	VIS/IR	250 - 1000	USA	2000	operational[2]
ENVISAT	ASAR	MW	30 - 1000	ESA	1999	back-up
EOS	AMSR	MW	11,600	USA	2000	back-up
QuikSCAT	SCAT	MW	25,000	USA	1998	experimental
ENVISAT	AATSR	VIS/IR	1000	ESA	1999	experimental
ENVISAT	MERIS	VIS/IR	300 - 1200	ESA	1999	experimental

[1] Great Lakes only; [2] subject to good quality ice algorithm

Anticipated sources of satellite data, 1997-2002. Operational status is defined as follows. *Operational* means that the data will be used as a primary source of data for operations with processing systems and communications established for accessing and analyzing the data. *Back-up* means that the data are candidates as a source of data should a primary data stream become unavailable. In addition, if these data sources are demonstrated to be available on an operational basis, it is possible that they could augment the existing operational sensors. *Experimental* means that the data are unlikely to be used operationally during the next 5 years, but that there is interest in ascertaining their potential for ice monitoring.